Distributed Spacecraft Crosslink Study

Part 1

Spectrum Requirements and Allocation Survey Report and Recommendations

5 June 2002

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Authorization

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June 2002

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Revision Log

This log identifies the versions and associated release dates of this document and summarizes the changes made for each revision.

Version	Date	Summary of Changes to Previous Version	Distribution
0.5	8 Feb 2002	Initial Draft	GSFC and ITT Industries
1.0	5 June 2002	Initial release; incorporates minor revisions	NASA, GSFC, and ITT Industries

Table of Contents

1 Findings & Recommendations

1.1 Purpose & Background

1.1.1 Background

Emerging spacecraft systems plan to deploy multiple satellites in various "distributed" configurations ranging from close proximity formation flying to widely separated constellations in both near-earth orbit and in deep space. Distributed spacecraft configurations provide advantages for science exploration and operations since many activities useful for missions may be better served by distributing them between spacecraft. For example, many scientific observations can be enhanced through spatially separated platforms, such as for deep space interferometry.

Operating multiple distributed spacecraft as a mission requires coordination that may be best provided through inter-satellite communications. The choice of frequency and lower layer protocols (physical and data link layers) for this link involves the mission operations and requirements, hardware availability, and regulatory considerations. The link may be in the radio frequency range or could involve infrared or optical communications.

Unlike existing "bent-pipe" relay networks supporting space missions, no standard or widely-used method exists for crosslink communications. Consequently, to support these future missions, the characteristics necessary for inter-satellite communications need to be examined, including frequency band, protocol, and technology considerations.

This report is one part of a three part study reviewing Distributed Spacecraft System (DSS) requirements for crosslinks and identifying recommendations concerning spectrum, standards, and technology. The three parts of the study are:

1. **Spectrum Requirements and Allocation Survey**: required spectrum, frequency band choices, and upgrades (if necessary)
2. **Requirements**: identifies requirements and examines existing protocols and standards
3. **Technology Roadmap**: the technology necessary to provide inter-satellite communications capability based on high-level requirements

1.1.2 Purpose & Scope

The objective of this task is to make a recommendation on the available frequency bands for crosslinks and the amount of spectrum allocations required for inter-satellite communications (crosslink) usage in the 2010 to 2020 time frame. The planned approach to carrying out the task is to use a sample of currently planned distributed satellite missions as the basis for developing quantitative projected estimates of numbers of future missions and their spectrum requirements. An existing spectrum usage survey will be performed to determine the constraints on potential spectrum frequency bands that will limit future crosslink frequency assignments. Interference impacts will be taken into account in arriving at the final recommendations. In addition, this task will support the development of appropriate Space Frequency Coordination Group (SFCG) recommendations.

1.2 Findings

Based on a review of distributed spacecraft missions, technical and mission assessments, and applicable radio regulations, this study finds the following:

- A survey of proposed space and earth science distributed spacecraft missions identified 39 possible missions in the 2002-2020 timeframe with 23 apparently requiring inter-satellite (crosslink) communications
  - Near-term distributed spacecraft missions concentrate on establishing formation flying capabilities with later missions exploiting autonomous operations through collective navigation and communications
  - Inter-satellite communication and navigation requirements are not well defined at this time especially for future missions, but requirements (e.g., data rates, path lengths) will likely vary significantly between missions
- Distributed spacecraft systems requiring inter-satellite (crosslink) information exchange falls into four data types or traffic each with varying levels of bandwidth requirements:
  - Navigation
  - Spacecraft health & status
  - Science data
  - Command data
- Based on the survey of distributed spacecraft missions and an assessment of data needs, the amount of radio frequency bandwidth required for all space and earth science crosslinks at any given time over the next 20 years is less than 120 MHz with a time varying need as indicated in Table 1-1.
  - Several missions may consider the use of free-space optical (laser) links especially for high-precision navigation, but since optical frequencies are not currently regulated they were not included in the bandwidth estimates

Table 1-1: Estimated Needed Space & Earth Science Crosslink Radio Frequency Bandwidth

Operational Intervals	Est. Max Bandwidth Requirements For Operational Missions (MHz)
2001 to 2005	27.3
2006 to 2010	90.7
2011 to 2015	107.3
2016 and beyond	116.6

- There are many frequency bands (from 400 MHz to over 100 GHz) allocated to services defined by the regulatory community in which a crosslink system that transfers information between distributed spacecraft shares characteristics including:
  - Earth Exploration-Satellite;
  - Space Operation;
  - Space Research;
  - Inter-Satellite; and,
  - Radionavigation and Radionavigation-satellite service (for signals transmitted solely for navigational purposes).

1.3 Recommendations

Based on the assessment and findings concerning space and earth science distributed spacecraft missions, this report recommends the following:

- The space and earth science community does not need to pursue new frequency allocations for non-relay inter-satellite communications at this time since existing allocations should provide sufficient spectrum to meet expected demands through 2020.
  - However, the space science community should continue to monitor the need for crosslink spectrum especially if a larger than expected number of missions or missions with larger crosslink requirements are planned.
- To satisfy regulatory considerations and to promote interoperability, distributed spacecraft missions implementing inter-satellite communications and navigation exchange (crosslinks) should seek assignments in the frequency bands listed in Table 1-2.

Table 1-2: Preferred Frequency Bands for Science Inter-Satellite (Crosslink) Communications

Band	Frequency Band	Allocation Status*
S	2025 – 2110 MHz	SPACE OPERATION EARTH EXPLORATION SATELLITE SPACE RESEARCH
	2200 – 2290 MHz	SPACE OPERATION EARTH EXPLORATION SATELLITE SPACE RESEARCH
Ku	14.5 – 15.35 GHz	Space Research (The 14.5-15.35 GHz band is on the agenda of WRC-03 for possible upgrade to primary status)
Ka	22.55 – 23.55 GHz	INTER-SATELLITE
	25.25 – 27.5 GHz	INTER-SATELLITE

* Primary allocations listed by CAPITAL letters; secondary in lower case.

- Careful consideration needs to be taken before using frequency bands other than those listed in Table 1-2 for inter-satellite communications since the operational environment may not be conducive for limiting interference or for obtaining global assignments (e.g., the 13.75-14.3 GHz band which will have significant fixed-satellite service operations)
- The space and earth science community should further review mission designs and the allocations in the UHF region (specifically in the range of 400-450 MHz) of the spectrum to ascertain whether an upgrade to an existing allocation or a new allocation (primary or secondary) is necessary to provide additional options to mission designers requiring low-power inter-satellite communications, including systems operating in deep space.

2 Distributed Spacecraft Missions and Crosslinks

2.1 Distributed Spacecraft Missions

Distributed satellite spacecraft missions consist of multiple satellites that interact and cooperate to achieve mission goals. A large segment of the distributed spacecraft will accomplish their interactions via direct communications between spacecraft via RF or optical crosslinks. These spacecraft will operate with varying degrees of autonomy thereby limiting the need for frequent ground segment intervention to carry out mission objectives. Other distributed spacecraft missions will collaborate by supplying data to the ground segment via space-to-ground links for the purpose of consolidation and reduction. These missions will require a high degree of ground segment interactions with the spacecraft to carryout the mission objectives. Since this report is concerned with crosslink communications, the distributed spacecraft missions that rely entirely on space-to-ground link communications will not be addressed. Two types of crosslink missions are considered in the report. These are distributed spacecraft constellation and formation flying missions.

Constellation missions typically involve satellites in orbits about a planetary body or the sun that share science information via crosslinks. They do not rely on each other for information required to make autonomous on-board orbital navigation corrections. Navigation data corrections that support spacecraft maneuvers are made via information obtained from the ground segment. Formation flying missions rely on crosslinks to exchange navigation data between spacecraft for the purpose of autonomous spacecraft navigational corrections. Formation flying missions typically maintain tight tolerances on the positions of there spacecraft in order to meet mission science objectives. The formation's navigation management function is located on one or more spacecraft and the members exchange navigation data and commands to allow real-time maintenance of the group's physical topology. Science and spacecraft health and status may be exchanged among the mission spacecraft members via the crosslinks.

2.1.1 Missions

A survey of distributed spacecraft missions was undertaken as a basis for arriving at recommendations for future distributed spacecraft crosslink frequency allocations. Table A-1 in Appendix A contains a list of planned distributed satellite missions for a time span that covers the next twenty years. Near-term plans for distributed spacecraft missions are concentrated on an effort to establish a formation flying space based test bed to incrementally develop the capabilities that lead to autonomous, collective navigation. The Orion program is a rapid, low cost demonstration that is geared for showing the capabilities of interactions, cooperation, and a common system wide behavior between formation spacecraft in the 2002 to 2006 time frame. Other programs such as the Magnetic Imaging Constellation (MAGIC), Magnetospheric Multiscale (MMS), Constellation-X, Laser Interferometer Space Antenna (LISA), and Planet Imager (PI) are planned to work in parallel to provide diverse, fully capable, and robust solutions that will support the needs of Earth and Space Science Communities over the next twenty years.

2.1.2 Classification of Missions

Distributed spacecraft missions consist of fleets of space vehicles that exhibit all or some subset of the following characteristics:

- Interact and cooperate to achieve mission goals,
- Collectively manage science data gathering,
- Collectively manage vehicle positioning,
- Evolve over time by extending and enchancing mission capabilities, and

- Operate autonomously over periods of time to minimize ground segment support.

Figure 2-1 illustrates distributed spacecraft mission classifications from a communications hierarchical perspective. Distributed spacecraft cooperation methods can be divided into two communications categories: ground link and crosslink coordinated information communications. Ground link communications allows information to be collected from each spacecraft via space-to-ground links. These distributed spacecraft do not exchange information directly with each other to meet the common objectives of the group. The ground segment collects and processes the information from each mission spacecraft and then it constructs a composite mission perspective both in the area of science and navigation operations. In general, missions operating in this category are highly dependent on the ground segment, which serves as a centralized controller for the distributed S/C. Some distributed spacecraft missions described as constellations cooperate via space-to-ground link communications alone.

Crosslink communications missions have a reduced dependence on ground segment control in comparison to the missions that rely entirely by the ground segment for science and navigation operations. They require minimal ground contact to obtain mission planning directives and to supply science data to the ground segment. Constellations and formation flying missions use crosslink communications to exchange data between spacecraft. Constellations that use crosslinks typically share information that is related directly to science data collection operations.

Unlike constellation missions which may or may not use a crosslink communications architecture, formation flying missions are predicated on the existence of inter-spacecraft crosslinks to operationally achieve the mission objectives. Formation flying spacecraft exchange navigation data and commands among mission spacecraft with the objective of maintaining high tolerances in the required positions of the spacecraft in order to meet mission science objectives. The communications architectures for missions can be varied in general. Two extremes identified in Figure 2-1 are the centralized and the distributed topologies. These topologies are depicted spatially in Figure 2-2.

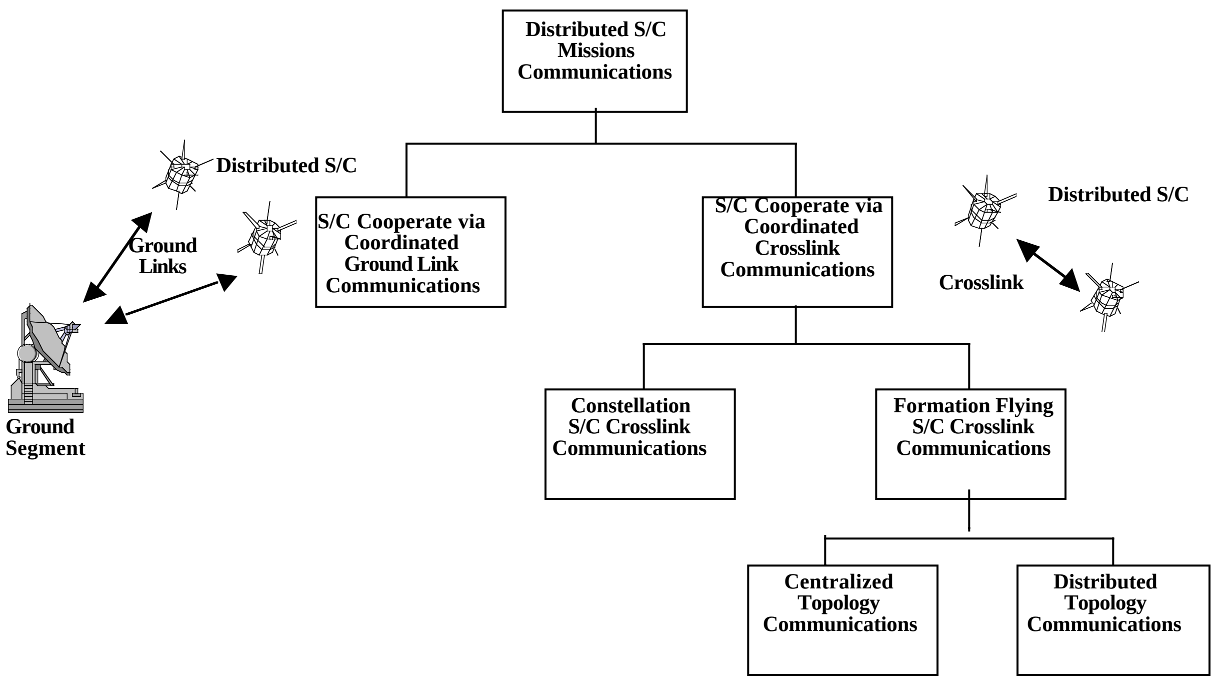
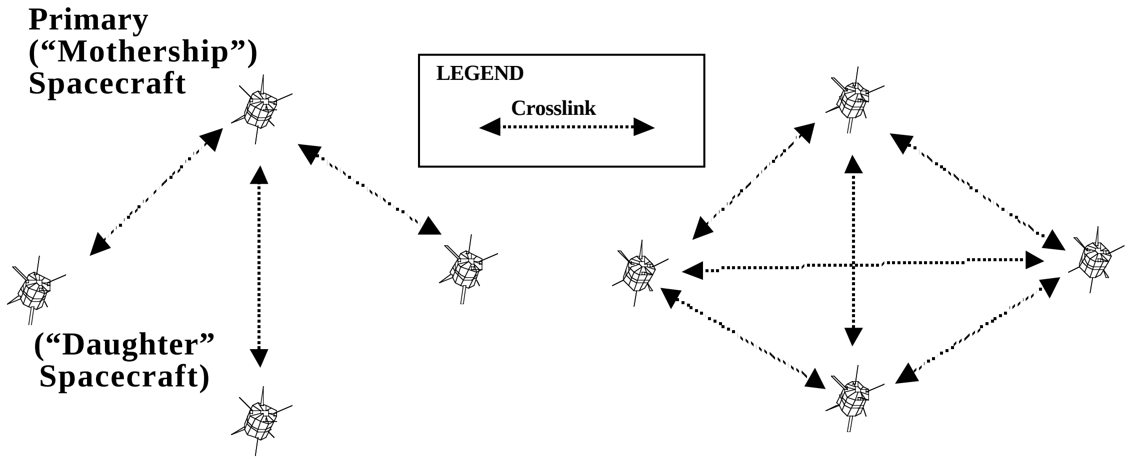


Figure 2-1: Distributed Spacecraft Communications Architecture Hierarchy



Centralized Formation Flying Topology *Distributed Formation Flying Topology*

Figure 2-2: Basic Formation Flying Communications Topologies

The centralized formation flying topology shown in Figure 2-2 consists of a "mothership" as the primary spacecraft, and "daughter" spacecraft as secondary spacecraft. The "mothership" acts as the control point for the formation. Centralized formation navigation and/or science processing takes place on the "mothership". Crosslinks serve as conduits for the daughter spacecraft to pass information to the "mothership" from the "daughter" spacecraft. Likewise, the "mothership" spacecraft supplies information to the "daughter" via the crosslinks. "Daughter" spacecraft do not communicate with each other via crosslinks. The "mothership" orchestrates mission objectives based on autonomous on-board formation control processing. The "mothership" is a single point of failure due to its unique capabilities and its centralized role within the formation.

The distributed formation flying topology shown in Figure 2-2 does not have a single point of control within the formation. Instead, all of the spacecraft have the same operations capabilities relative to the autonomous maintenance of the formations collective objectives. The crosslinks are used to share spacecraft navigation and science related information with all other spacecraft in the group. Unlike the centralized formation, the distributed formation does not have a single point of failure since all the spacecraft have the same functionality relative to the overall formation. This robustness comes at the expense of more sophistication built into each spacecraft. The failure of a few spacecraft in missions with large number of spacecraft can usually be tolerated without requiring that the mission be aborted.

Hybrid formations consisting of sub-groupings of the centralized and distributed topologies can also exist for large formations. For example, local groupings of spacecraft in a large formation may operate as distributed sub-topologies. Each sub-topology could then report the local distributed formation information to a "mothership" that coordinates all the sub-groups from a high-level centralized topology perspective. In some formation flying situations, the topologies might evolve with time as the formation analyzes science data and reacts in an autonomous manner to the real-time changing circumstances that arises as the mission unfolds.

Distributed spacecraft systems can be grouped into several mission types based on the location of the spacecraft and the objectives of the mission. These types are Earth Science Mission, Technology Demonstrator, and Space Science Mission. Earth Science Missions are located in the Near-Earth environment with missions typically placed in Low Earth Orbits (LEOs), Medium Earth Orbits (MEOs), High Earth Orbits (HEOs), or Geosynchronous Earth Orbits (GEOs). The objectives of these missions are directed at obtaining information about the Earth and the Earth-related physical phenomena that extended beyond the Earth into the region of space surrounding it. Examples of the

Earth's physical features under observation by these missions are surface, atmospheric, gravitational field, and magnetic field. Technology Demonstration Missions are aimed at demonstrating new technologies that can be deployed in future distributed satellite missions. Space Science Missions are situated in inter-planetary space or around other planets. Examples of Space Science Missions are stellar interferometry, solar atmospheric monitoring, solar system planetary monitoring, and extra-solar system planetary observing missions. Further classification separates missions that plan to use crosslink communications from those that will function without crosslinks.

2.2 Inter-Satellite Communications for Distributed Spacecraft Missions

2.2.1 Overview

Communications between distributed spacecraft will be achieved by the use of radio frequency (RF), infrared, and optical crosslinks. RF crosslinks are defined as a means of providing an Inter-Satellite radio communications service. This study concentrates only on RF crosslinks between science satellites in the same or different missions. It does not include crosslinks between science satellites and communications relay satellites used by some missions as an intermediate satellite to exchange information between the distributed satellites and their mission ground segments.

2.2.2 Crosslink Capabilities

Introduction

The capabilities needed for mission crosslink communications are dependent on mission goals, operations strategies, spacecraft physical and cost considerations as well as the topology of the mission spacecraft. Bandwidth requirements derived from mission science requirements are the driving factor in the development of crosslink requirements. For example, formation flying missions that have a centralized topology such that a "mothership" frequently processes large volumes of data collected by the "daughter" spacecraft will require crosslink that support significantly higher bandwidth than those missions where the sole function of the crosslink is to infrequently exchange low volume navigation and health and status information between the spacecraft. The physical aspects of the crosslink such as the antenna gain and the power of the transmitter must be selected in order to satisfy the free space propagation constraints of the mission. Small spacecraft are limited to small antennas that typically do not support wide bandwidths. As such, low-cost missions with centralized topologies that require high date rate crosslinks may not be able to meet the bandwidth requirements due to the limited crosslink equipment options. Figure 2-3 shows the general process for assessing a crosslink communications system for a distributed spacecraft mission whose bandwidth requirements, physical constraints, technological constraints, and cost constraints are provided as part of the mission objectives and operations strategies.

Multiple Access Capabilities

The number of spacecraft in the mission architecture imposes restrictions on the operations of the crosslinks. These constraints are manifested in the multiple access techniques used by the mission crosslink communications system to manage the each spacecraft's access to the shared frequency resource. Multiple crosslinks that operate at the same frequency require that a time sequenced protocol be implemented among all the spacecraft in order to avoid the interference that results from attempted simultaneous transmissions. This constraint reduces the overall mission information throughput performance since each spacecraft must wait their turn to access the shared frequency.

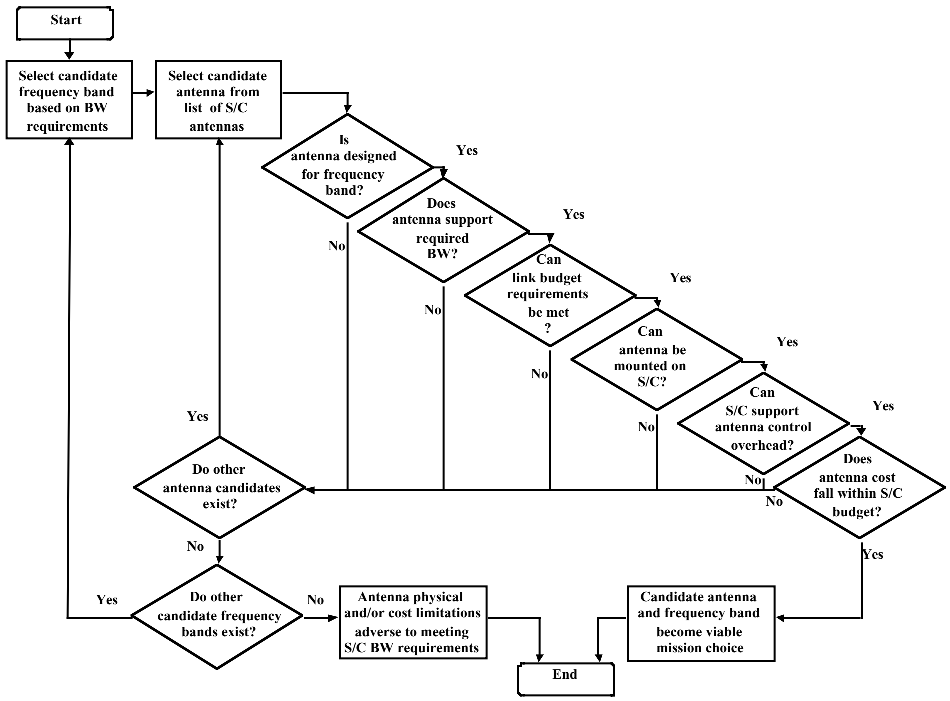


Figure 2-3: Process for Assessing a Candidate Crosslink Communications System

This throughput reduction can be avoided by having crosslinks operate at different frequencies. However, this solution comes at the added expense of unique transceiver frequency implementations which in turn drives up the cost of the spacecraft. In addition, more of the available frequency spectrum must be reserved for the mission. Simultaneous transmissions can also be achieved at the same center frequency using spread spectrum techniques. Even with spread spectrum techniques, there is a limit as to how many simultaneous broadcast can occur simultaneously due to the mutual noise floor making it necessary to have large distributed systems partitioned into frequency subgroups to avoid exceeding the noise limit. The spread spectrum technique is inherently wideband due to the pseudo-random spreading modulation that is superimposed on the signal to achieve the spread. As such, spread spectrum crosslinks require relatively wide segments of the existing spectrum.

Crosslink Bandwidth Capabilities

Distributed spacecraft crosslink bandwidth capabilities depend on the science, navigation, command, and spacecraft health and status data exchanged between spacecraft. These four crosslink data types can vary significantly in terms of volume and transmission frequency from mission to mission.

Formation flying missions requiring centralized, on-board processing of science data gathered by member spacecraft can require the widest crosslink bandwidths. For these missions, science data gathered by formation spacecraft is transmitted to a centralized processing facility on-board the “mothership” for reduction. In the case of science imaging missions, this can result in large volumes of image data being transferred frequently across crosslinks to the “mothership”. By contrast, some formation flying missions may choose to process all of the science data on the ground using downlink capabilities to off load the science data. These missions types will require significantly less bandwidth capability on their crosslinks than the centralized processing type described above.

The volume and frequency of the navigation data is tightly coupled to the nature of the mission. For example, interferometric formation flying spacecraft missions with centralized topologies typically require that tight relative spacecraft position tolerances (some measured in terms of wavelengths of the science signals) be maintained in order that the interferometer can function properly. This requires that the formation spacecraft continuously monitor their positions and attitudes and report the navigation measurements via crosslink data exchanges for assessment by an overall formation topology management function within the formation. This function in turn provides navigation corrections to the spacecraft to command any drifting spacecraft back within the mission position tolerances via guidance system operations. The tight loop-back communications associated with this scenario requires significantly greater crosslink navigation bandwidth requirements than those missions requiring kilometer level positional accuracy.

Broadcasting health and status messages across the crosslinks allows members of a distributed system to evaluate the operational state of the transmitting spacecraft in order to determine if the on-board equipment is functioning properly. This information allows the other members of the distributed spacecraft system to include or ignore data that is being received from another spacecraft. In general, health and status data is very low volume and would be broadcast less frequently than the science and navigation data. As such, health and status data is a very narrow bandwidth contributor to the overall crosslink bandwidth when science, navigation, and health and status data are considered together.

2.2.3 Classification of Crosslinks

Missions will vary in terms of science objectives, spatial location, duration, and spacecraft complexity. However, from a communications perspective, there are a number of basic features in common to all missions. Table 2-1 shows the taxonomy of crosslinks characterized by inter-satellite communications distances and maximum data rates for information transferal over the crosslink. This method of classification provides a means of categorizing all missions on the basis of their crosslink maximum signal path length and maximum data rate requirements. These two parameters, when taken together, form a primary constraint on minimum transmit power level and antenna gain needed to provide the signal quality needed at the receiving end of the crosslink to close the crosslink communications loop. Secondary communications factors such as inherent equipment noise levels and code error correction techniques further refine the quality of the crosslink from an operational performance perspective. Replacing the maximum signal path length and data rate with the class indicator listed in Table 2-1 provides a single index of crosslink classification that spans the range of all conceivable distributed spacecraft mission possibilities.

Table 2-1: Classification via Crosslink Communications Parameters

	Maximum Inter-Satellite Communication Distance		
Maximum Data Rate	<10 km	10 km – 1000 km	>1000 km
<100 kbps	Class 1a	Class 1b	Class 1c
100 kbps – 1 Mbps	Class 2a	Class 2b	Class 2c
1 Mbps – 10 Mbps	Class 3a	Class 3b	Class 3c
10 Mbps – 100 Mbps	Class 4a	Class 4b	Class 4c
100 Mbps – 600 Mbps	Class 5a	Class 5b	Class 5c
>600 Mbps	Class 6a	Class 6b	Class 6c

3 Inter-Satellite Communication Crosslink Bandwidth Requirements

3.1 Bandwidth Estimation Approach

An important step in identifying spectrum for space and earth science crosslinks is determining the maximum amount of bandwidth required to satisfy the expected number of distributed spacecraft missions. Figure 3-1 shows the high-level process used to estimate the maximum crosslink bandwidth requirements in five year intervals over the next two decades. The process is divided into several steps:

- Generate Database of Distributed Spacecraft Missions. To collect this data, the study conducted a survey of proposed distributed spacecraft missions. The survey gathered as much data as possible based on the preliminary plans or concepts for missions.
- Evaluate Crosslink Data Types. Based on formation flying communication operations concepts and expected mission needs, the types and amounts of data transmitted across crosslinks were identified.
- Derive Crosslink Statistical Parameters. An assessment of the data types and mission database resulted in mission crosslink parameters that were extracted or inferred from the descriptions. Cross comparison of parameters within a mission and across missions produced emerging qualitative and quantitative crosslink information based on stated or inferred spacecraft size, cost, orbital constraints, crosslink signal path lengths, etc.
- Bandwidth Estimation Calculation. The probable number of simultaneously operational crosslinks for each mission was estimated based on mission architecture and objectives considering the available types of multiple access alternatives available and the cost associated with these techniques. The number of crosslinks and the statistical crosslink parameters were then used to calculate the estimated bandwidth requirements for space and earth science mission crosslinks.

3.2 Distributed Spacecraft Mission Survey

3.2.1 Survey Description and Summary

As discussed in Section 2, a distributed spacecraft survey identified proposed missions that intend to fly multiple spacecraft and utilize crosslinks. Table 3-1 summarizes the identified number of distributed satellite missions planning to use crosslinks for a time span that covers the next twenty years while Table A-1 in Appendix A provides additional details for each mission. Near-term plans for distributed spacecraft missions are concentrated on an effort to establish a formation flying space based test bed to incrementally develop the capabilities that lead to autonomous, collective navigation. High-level distributed space mission descriptions were obtained primarily from GSFC Code 570 mission database, Internet mission sites, and additional open literature or conference information. These descriptions form the input data to the estimation process.

Given the likelihood that several of the planned missions will not launch and the fact that missions that will be developed are not yet defined, especially in the later five year intervals, the study also estimated the likely amount of actual operational missions. Table 3-2 and Table 3-3 summarize this estimate. Consequently, the bandwidth estimate, described in Section 3.5, uses the estimated number of operational missions derived from the survey.

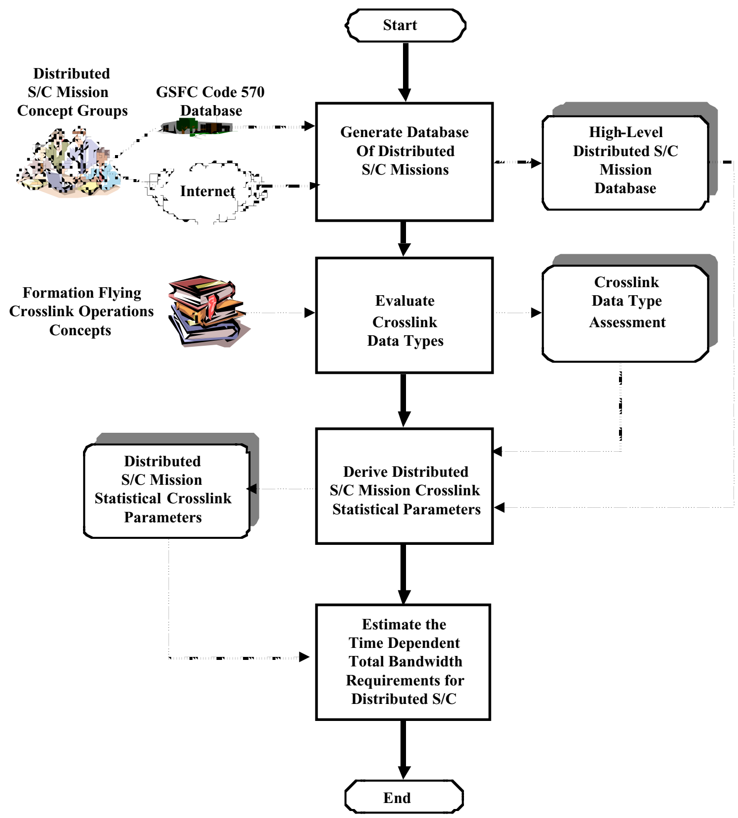


Figure 3-1: Crosslink Bandwidth Estimation Approach

Table 3-1: Number of Identified Distributed Spacecraft Missions Expected to Use Crosslinks

Mission Launch Date Intervals	Constellations	Centralized Formations	Distributed Formations
2001 to 2005	1	1	7
2006 to 2010	1	2	5
2011 to 2015	0	2	1
2016 and beyond	0	2	1

Table 3-2: Estimated Fraction of Operational Missions Identified by the Survey

Mission Launch Date Intervals	Constellations	Centralized Formations	Distributed Formations
2001 to 2005	1.0	1.0	1.4
2006 to 2010	0.5	0.8	0.8
2011 to 2015	0.4	0.4	0.2
2016 and beyond	0.3	0.3	0.1

Table 3-3: Estimated Number of Operational Space & Earth Science Distributed Spacecraft Missions Using Crosslinks

Mission Launch Date Intervals	Constellations	Centralized Formations	Distributed Formations
2001 to 2005	1	1	5
2006 to 2010	2	3	6
2011 to 2015	2	5	5
2016 and beyond	2	7	10

3.2.2 Mission Crosslink Classes and Projections

Distributed spacecraft systems requiring crosslinks communications in the time frame from 2002 to 2020 have been analyzed and the detailed results of the survey are presented in Appendix A. Table A-2 list the crosslink communications classes that are estimated to be viable possibilities for a number of missions where sufficient information was provided to derive the various crosslink classes that could be used to meet mission objectives. The shaded area of Table 3-4 summarizes the estimated transmitter classes that are possible given 1 W and 10 W crosslink systems. Additional discussion of crosslink system design is described in Appendix A.

Table 3-4: Estimated Crosslink Class Requirements from 2002 to 2020

	Maximum Inter-Satellite Communication Distance		
Maximum Data Rate	<10 km	10 km – 1000 km	>1000 km
<100 kbps	Class 1a	Class 1b	Class 1c
100 kbps – 1 Mbps	Class 2a	Class 2b	Class 2c
1 Mbps – 10 Mbps	Class 3a	Class 3b	Class 3c
10 Mbps – 100 Mbps	Class 4a	Class 4b	Class 4c
100 Mbps – 600 Mbps	Class 5a	Class 5b	Class 5c
>600 Mbps	Class 6a	Class 6b	Class 6c

3.3 Inter-Satellite Communication (Crosslink) Data Types

As described in the following four subsections, the four data type contributors to distributed spacecraft crosslink message traffic are navigation, spacecraft health and status, science data, and command data. The volume and frequency of transmissions of this information determines the bandwidth requirements for a crosslink. In general, all four types of data flows can occur sequentially on the crosslink. This suggests a time varying data rate as the crosslink transitions between transporting each of the four data types. Depending on the classification of the distributed system, regular navigation data may or may not be required to be exchanged between spacecraft. For example, distributed spacecraft in a constellation do not maintain their positions by exchanging navigation data between each other. On the other hand, formation flying satellites rely heavily on the sharing of navigation information to maintain the spatial requirements of the formation's topology under the continual influence of perturbing forces that act on the individual spacecraft to introduce perturbations to the formation's topology.

The transmission rates for each of the four crosslink data types can be characterized in terms of bandwidth descriptions. As the data rate requirements increase for the crosslink service, the amount of bandwidth required for the transmission also increases. Bandwidth requirements are described in terms of the following attributes: narrow, medium, and wide. Table 3-5 lists the qualitative descriptions of the bandwidths used in this survey with respect to the quantitative data rate intervals that are associated with the bandwidth descriptions.

Table 3-5: Bandwidth and Data Rate Equivalences

Bandwidth	Maximum Data Rate
Narrow	<100 kbps
Medium	100 kbps – 1 Mbps
	1 Mbps – 10 Mbps
Wide	10 Mbps – 100 Mbps
	100 Mbps – 600 Mbps
	>600 Mbps

3.3.1 Science Data

Estimates of science data rates for a mission presents the greatest challenge given the proposed distributed satellite mission descriptions available today. The accuracy of the estimates depends on the knowledge of how the science data will be processed in the distributed spacecraft system. One extreme consists of a number of distributed spacecraft collecting common science data and periodically dumping it to ground stations with no space segment processing. This scenario requires no bandwidth on any existing crosslinks for science data transmissions since the spacecraft do not share science data. At the other extreme, a formation flying mission can have a centralized science data processor that requires the forwarding of data collected at all the other spacecraft to central location within the formation via crosslink transmission. Missions with hybrid formation flying topologies consisting of a mixture of centralized and distributed topologies may require that some of the crosslinks be used to relay science data from several spacecraft to a centralized processing location. The bandwidth requirements can be significant in these situations if the volume and frequency of science data transmission are both high, especially for missions collecting imaging information (e.g., interferometric and optical mapping missions). These missions may require wide bandwidth crosslinks with up to 10 Mbps data rates. If a single frequency is implemented for all crosslinks, then time constraints are levied on the size of the time windows available for each crosslink science data exchange. The need to burst the science data in missions with short crosslink transmission time intervals becomes more and more important as the number of spacecraft in the formation increases. Bursting requirements further increase the bandwidth requirements for the crosslinks. Therefore, the method chosen by a mission to manage its science data processing plays a crucial role in determining whether or not the bandwidth requirements will be significant for that mission. The method employed in this survey for estimating the planned distributed spacecraft science data bandwidth capabilities is discussed in detail in Section 3.2.

3.3.2 Navigation Data

Formation flying spacecraft require navigational tolerances on the positions and attitude of the spacecraft relative to a model topology. Deviations from the model topology must be constantly assessed since perturbing forces act on the spacecraft and adjustments must be made to bring the formation back into accepted tolerances. This entails sharing of navigational data among the spacecraft using crosslink communications. Navigation data can contain measured absolute position, relative distance of separation, velocity, attitude, rotation, and time information. Assuming high precision binary data representations of these quantities in the crosslink navigation messages, the maximum amount of data in a navigation message is on the order of 10^3 bits. Depending on mission objectives, the frequency of broadcast of this information over a crosslink can vary widely from seconds for tightly coupled spacecraft to minutes for formations with wide navigational tolerance requirements. This places the estimated maximum navigation data rate at 1 kbps and the transmission can be continuous for tightly coupled formations. Therefore, the estimated navigation data requirements for formation flying crosslinks can be characterized as having a very narrow bandwidth as well as being an insignificant contributor to the overall bandwidth requirements for a crosslink that also carries science data.

3.3.3 Health & Status Data

Health and status information consists of engineering binary indicators and digitized measurements associated with the spacecraft equipment performance monitoring. The amount of this information depends upon the complexity of the equipment on the spacecraft, the ability to monitor its performance, and the need to share the information with other spacecraft. In general, an order of magnitude estimate of 10^3 bits is sufficient for most mission spacecraft to convey all its status information in a binary representation in a single message. Assuming that the need to report spacecraft status is on the order of minutes, it follows that an estimate for spacecraft health and status maximum data rate is on the order of 10^{-2} kbps. The health and status bandwidth requirements for a crosslink can be described as being very narrow.

3.3.4 Command Data

Crosslink command data is information that is provided to distributed spacecraft from a centralized location within the distribution. The information can consist of formation navigation corrections and science event scheduling information. Command data invokes the concept of a master-slave architecture within the distribution that reduces the chances for its existence outside of formation flying missions.

In tightly coupled centralized formation flying missions, formation navigation corrections can occur frequently in order to constantly fine-tune the alignment of the spacecraft within the position and attitude requirements of the topology. A centralized formation can have a common control process that evaluates the navigation data received from each of the subordinate spacecraft and issues navigation correction commands to each spacecraft via the crosslinks. Since the navigation correction data impacts the same position and attitude parameters as those described in the navigation data bandwidth requirements section above, it is estimated that for a tightly coupled formation, the maximum data rate for the navigation correction data is on the order of 1 kbps and can be continuous for tightly coupled missions. The maximum navigation correction command data bandwidth requirements for a crosslink can be described as being narrow.

Distributed spacecraft missions with crosslinks may choose to use one of the spacecraft in a grouping of spacecraft as a single point of contact and for relaying science event scheduling information to all the spacecraft. In this case, the science command information is received by one spacecraft and distributed to the remaining spacecraft via the crosslinks. The updating of science event scheduling can be described as infrequent. The time interval between new event scheduling perspectives is on the order of a day for most distributed spacecraft missions. The maximum amount of data need to be transmitted on a crosslink is estimated to be less than 10^4 bits.

3.4 Crosslink Statistical Parameter Estimation

An assessment of the distributed spacecraft missions identified by the survey (Appendix A) and the data types identified by the operations concepts (Section 3.3) provides a high-level perspective of crosslink maximum bandwidth requirements that is summarized in Table 3-6. Table 3-6 groups these mission architectures into formation flying and constellation with formation flying being further subdivided into centralized and distributed topologies. Each mission was assessed in terms of the probability that each of four crosslink data types (science, navigation, health and status, and command data) would be present on a crosslink based on mission objectives and the likely communications architectures. The four data types that can be present on a crosslink are described as a function of narrow, medium, and wide bandwidths for each architecture type. Each data type for each architecture is assigned a qualitative likelihood of being present based on a survey of the planned mission types.

The next to the last row in the table provides a quantitative summary of the estimated probability of a maximum bandwidth requirement being present among a particular mission architecture type. The last row in the table corresponds to the estimated maximum data derived from the data type descriptions in the previous four sections.

Table 3-6: Estimated Probability of Distributed Spacecraft Mission Crosslink Maximum Bandwidth Capabilities

Architecture	Constellation			Formation Flying					
Topology	**Not Applicable**			**Centralized**			**Distributed**		
Bandwidth	**Narrow**	**Medium**	**Wide**	**Narrow**	**Medium**	**Wide**	**Narrow**	**Medium**	**Wide**
Science Data	High	Low	Low	Low	Low	High	Low	Low	Low
Nav Data	Low	Low	Low	High	Low	Low	High	Low	Low
Health and status Data	Low	Low	Low	High	Low	Low	High	Low	Low
Command Data	Low	Low	Low	High	Low	Low	Low	Low	Low
Bandwidth Requirement Probability (%)	80	10	10	60	10	30	80	10	10
Estimated Avg. Max. Data Rate (Mbps)	0.01	1	10	0.01	1	10	0.01	1	10

3.5 Distributed Spacecraft Crosslink Maximum Bandwidth Estimation

3.5.1 Calculation Overview

Estimating the total bandwidth required for space and earth science distributed spacecraft missions using crosslinks requires a simple calculation using the probable number of simultaneously operational crosslinks, the probabilities that mission crosslinks need narrow, medium, or wide bandwidth communication capabilities, and the associated maximum data rate with the narrow, medium, or wide bandwidth capability. Equation 3-1 defines the method of estimating the total maximum data rate from which the total bandwidth requirements for all of the distributed spacecraft missions reviewed in this survey was derived.

$$\text{Total Max Data Rate} = \sum_{j=1}^{3} N_j \times \left[\sum_{i=1}^{3} p_{ij} \times MDR_i \right] \qquad \text{(Eq. 3-1)}$$

The subscript j corresponds to the crosslink architecture type (j = 1,2, and 3 corresponds to constellation, centralized formation, and distributed formation, respectively). The subscript i corresponds to the bandwidth category (i = 1,2, and 3 corresponds to narrow, medium, and wide bandwidths, respectively) that are shown in Table 3-6. The maximum data rate (MDR_i) for each bandwidth category is determined from the information presented in Sections 3.3 and 3.4 and summarized in Table 3-6. The probability that a particular maximum bandwidth will be required for a given architecture is represented by p_{ij} (Table 3-6). The total number of crosslinks operating at any given time within an architecture type is given by N_j. N_j is a function of the number of missions within each distributed spacecraft architecture, the number of possible crosslinks that can be formed, and the likelihood that crosslink multiple access techniques for a given mission will support simultaneous transmissions.

3.5.2 Number of Simultaneous Crosslinks

The probable number of simultaneously operational crosslinks for each mission in the survey was estimated based on the number of spacecraft, architecture, and objectives considering the available types of multiple access alternatives available and the cost associated with these techniques. Since the distributed spacecraft missions will launch at different times and have different lifetimes, the total maximum data rate expressed in Equation 3-1 will vary with time. Table 3-7 shows a summary of the estimated maximum number of simultaneous crosslinks for the identified missions broken into time intervals of five year intervals between 2001 and 2020 while Table 3-8 shows an extrapolation of the estimated total number of simultaneous crosslinks based on the estimated number of missions in Table 3-3 and mission maximum life expectancy of 10 years. The number of simultaneous crosslinks may vary significantly if missions with large number of satellites (> 12) are developed. The identified mission set includes only a few such mission.

Table 3-7: Estimated Maximum Number of Simultaneous Crosslink Transmissions as a Function of Mission Launch Date (Identified Missions Only)

Mission Launch Date Intervals	Constellations	Centralized Formations	Distributed Formations
2001 to 2005	6	1	10
2006 to 2010	3	2	39
2011 to 2015	0	4	1
2016 and beyond	0	5	2

Table 3-8: Estimated Maximum Number of Simultaneous Crosslink Transmissions as a Function of Mission Launch Date

Operational Intervals	Constellations	Centralized Formations	Distributed Formations
2001 to 2005	6	2	20
2006 to 2010	10	6	47
2011 to 2015	10	10	20
2016 and beyond	10	18	40

3.5.3 Geometric and Interference Considerations

The geometric distribution of missions and the likely interference between crosslink transmissions can greatly affect the required bandwidth needed for crosslinks. For example, missions operating in deep space will likely not cause or encounter interference from Low Earth Orbiting (LEO) missions. In addition, the use of directional antennas or multiple access techniques can greatly expand the number of crosslinks that can be supported in a given bandwidth.

The amount of crosslink mission interference to be expected from distributed spacecraft crosslink operations is a function of the number of transmitters operating in the same frequency band, the bandwidths of the transmissions, antenna patterns, the spatial distribution of the missions, and the operational time periods. The spatial distribution of the crosslink missions surveyed in Appendix A can be viewed from a perspective that assumes that the maximum crosslink signal path length is restricted to identifiable spatial volumes in many instances. Table 3-4 provides a summary of the potential crosslink mission classes that may be implemented based on the survey results presented in Appendix A for those missions providing sufficient information from which estimates can be made. The classes characterize the upper bounds on the bandwidths and signal path lengths that can be reasonably be associated with the crosslink missions. Bounds on the signal path lengths can be coupled with mission types to provide a compartmentalized perspective of crosslink communications.

Table 3-9 presents a spatial (regions in space) and temporal (launch date) distribution of the surveyed distributed spacecraft missions including several that do not indicate the need for crosslinks. LEO, MEO, HEO, and GEO missions can, in many instances, be viewed as being restricted to layered shells of varying mean altitude above the Earth. The use of low cost, low gain crosslink antennas will result in opportunities for interference between these missions within and across the series of orbital shells. The use of high cost, high gain crosslink antennas could result in fewer opportunities for inter-mission crosslink interference at a significant increase in cost of the crosslink communication system. Mission spacecraft with highly elliptical orbits will a traverse a number of the shells for limited periods of time allowing for more opportunities for inter-mission interference.

Lunar orbiting missions have small probabilities of crosslink interference with Earth orbiting missions due to limitations in crosslink signal path lengths and antenna beam patterns that will probably emphasize breadth of angular crosslink coverage over distance in most mission implementations. The power requirements needed to induce intereference at such large distances should not in general be implemented in the crosslink communications system design since a mission's spacecraft separation will not be on the order of magnitude of Earth-Moon distances. The same situation is true for the Earth orbiting mission interfering with Lunar missions.

Missions placed at far Earth-Sun libration points (e.g., L_2 point) will be significantly further from the Earth than the Moon thus making interference between missions located in the Earth, Moon, and L_2 regions very improbable. However, L_2 missions may have a relatively high probability of crosslink interference amongst themselves. The spatial isolation of solar orbiting missions relative to the other regions described above makes the likelihood of crosslink interference small among solar orbiting missions as well as with the missions in the other regions.

Table 3-9: Spatial Distribution of Identified Distributed Spacecraft Missions as a Function of Launch Dates

Mission Survey Launch Date Intervals	LEO	MEO	HEO	GEO	LUNAR ORBIT	SOLAR L_2 ORBIT	SOLAR ORBIT
2001 to 2005	3		1		1		1
2006 to 2010	6		2	1	1	1	1
2011 to 2015	3		1	1		2	2
2016 and beyond	1	1	1			2	2

Since mission design will likely limit the chance for interference between missions in Earth orbit and missions operating in other regions, the total bandwidth required for missions should be based on the total number of simultaneous crosslinks in Earth orbit. Table 3-10 indicates the estimated number of simultaneous crosslinks in Earth orbit based on Table 3-8 (estimated operational crosslinks for all missions) and Table 3-9, where 62% of the identified missions are in Earth orbit. Although spacecraft design practices (e.g., power, antenna design) can be employed to limit interference, thus increasing the number of crosslinks that could be supported by a given bandwidth, the values in Table 3-10 correspond to the factor N_j in Equation 3-1.

Table 3-10: Estimated Maximum Number of Possible Simultaneous Crosslink Transmissions in Earth Orbit

Operational Intervals	Constellations	Centralized Formations	Distributed Formations
2001 to 2005	6	2	13
2006 to 2010	7	4	39
2011 to 2015	7	7	13
2016 and beyond	7	12	25

3.5.4 Bandwidth Estimate

Evaluating Equation 3-1 using the information presented in Table 3-6 (parameters p_{ij} and MDR_i) and Table 3-10 (parameter N_j) yields the distribution of aggregate maximum crosslink bandwidth requirements presented in Table 3-11. The bandwidth estimate assumes a binary modulation format; consequently, the use of higher order modulations would reduce the required bandwidth. The values presented in Table 3-11 assume that the maximum life expectancy of a crosslink mission will be 10 years.

Table 3-11: Estimated Maximum Crosslink Required Bandwidth

Operational Intervals	Est. Max Bandwidth Requirements For Missions Launched (MHz)	Estimated Max Bandwidth Requirements For Operational Missions (MHz)
2001 to 2005	27.3	27.3
2006 to 2010	63.4	90.7
2011 to 2015	43.9	107.3
2016 and beyond	72.7	116.6

4 Inter-Satellite Communication Frequency Allocations

4.1 Overview

The appropriate frequency band or bands is an important part of any recommendation for inter-satellite communications. Several technical parameters (see Appendix A for more details) influence the identification of frequency bands useful for cross-links including:

- Location of distributed spacecraft communications operations (i.e., near-earth vs. deep space);
- Bandwidth, the amount needed for the required data rates and multiple access techniques;
- Directionality of link (i.e., uni-directional or bi-directional, asymmetric or symmetric);
- Number of channels and/or number of links in the local system network;
- Propagation effects, including free space loss;
- Antenna size, mass, beamwidth, and gain, which can vary greatly depending upon frequency;
- Link performance, including required power, which is affected by data rate, propagation, and antenna characteristics;
- RF (or infrared and optical) component availability; and,
- Component mass and power requirements.

Besides these technical considerations, international and national spectrum regulations are an important consideration when identifying spectrum or making frequency assignments for distributed spacecraft inter-satellite communications. Based on a technical assessment and the bandwidth estimate from Section 3, no one frequency band meets the needs for all distributed spacecraft communication classes, so several frequency bands need to be identified. Regulatory factors and criteria necessary for selecting preferred bands include:

- Primary allocation or high probability of obtaining a primary allocation for a radiocommunication service or services appropriate for space-to-space cross link systems;
- High probability that the bands will not be reallocated to other services in the foreseeable future;
- Use of the band(s) for space-to-space cross-links will contribute to civilian space agency's ability to retain access to the band(s) in the face of intense international competition for spectrum; and,
- Availability of space qualified hardware.

This section will explore the service classification and associated allocations to determine the appropriate frequency bands that are available for use by space and earth science distributed spacecraft inter-satellite (crosslink) communications.

4.2 Service Classification

The International Telecommunication Union (ITU), as specified in the Radio Regulations, defines a set of services according to shared characteristics that categorize systems utilizing radio waves. To promote an orderly and efficient use of the radio frequency spectrum, frequency bands are reserved for use by one or more services under specified conditions. These "allocations" for use by terrestrial and space radiocommunication services, in combination with other provisions of the Radio Regulations, promote the efficient use of the spectrum by ensuring that compatible systems which do not cause unacceptable interference operate together within a frequency band. The other technical and administrative provisions of the Radio Regulations that promote compatibility between systems include, for example, power flux-density limits, limits on the e.i.r.p. and transmitter power of stations, and coordination procedures. Several service definitions and related terms, including the definition of a radiocommunication service, are listed in Table 4-1.

When a radio transmitter or receiver, known as a “station,” is considered for authorization to operate at a specific frequency, known as an “assignment,” the station should share the characteristics of a service allocated to the relevant frequency band. Stations operating on distributed spacecraft that transfer information between science spacecraft share the characteristics with the following services:

- Earth Exploration-Satellite;
- Space Operation;
- Space Research;
- Inter-Satellite;
- Radionavigation and Radionavigation-satellite service (for signals transmitted solely for navigational purposes).

In addition to an appropriate service designation, the direction of transmission may also be defined by the allocations. Consequently, the following allocation options are available for crosslinks: (i) allocation to a space service (Space Research, Space Operation, or Earth Exploration-Satellite) with a designation of a "space-to-space" link; (ii) allocation to the space service (Space Research, Space Operation, or Earth Exploration-Satellite) without a restriction on the direction of transmission; (iii) allocations to the Inter-Satellite service; and (iv) allocations to radionavigation-satellite service (for signals transmitted solely for navigational purposes). Some allocations for the Space Research and Earth Exploration-Satellite services limit the operations to passive systems, thus precluding crosslinks. Finally, the Space Research service may also be limited to deep-space systems, precluded near-Earth systems or systems that may interfere with the sensitive reception of deep space signals.

Other options may also be available for crosslinks such as those bands associated with unlicensed operations or those bands where crosslinks do not cause interference to systems operating in accordance with the Table of Frequency Allocations. Both national regulatory agencies and the international Radio Regulations allow exceptions for systems that do not conform to the applicable allocations. For government systems in the United States, exceptions must be recommended by the IRAC Spectrum Planning Committee (SPS) and approved by the NTIA. These exceptions are granted on the condition that: (i) protection of the system from unacceptable interference cannot be assured and (ii) emissions must be terminated if interference is caused to other systems operating in accordance with the Radio Regulations. Authorization for systems not in conformance with the allocation are often granted as an “experimental” license. Consequently, other frequencies are possible for crosslinks especially for low-power operations or operations beyond the confines of Earth orbit. Missions should only consider such frequency bands if science or technical criteria require the use of those frequencies.

4.3 Existing Allocations & Regulations

4.3.1 International Allocations

Based on the available service options discussed in the previous section, Table 4-2 identifies those frequency bands already available for use by cross-links as well as other frequency bands allocated to space services (e.g., Space Research) even if only designated for space-Earth links. Table 4-2 also lists a sampling of other bands not allocated to space services, such as the unlicensed Industrial, Scientific and Medical (ISM) bands, that may be considered for space cross-links depending upon the interference potential to other systems and services.

Table 4-1: Selected ITU Radiocommunication Definitions

Term or Service	Definition
allocation (of a frequency band)	Entry in the Table of Frequency Allocations of a given frequency band for the purpose of its use by one or more terrestrial or space *radiocommunication services* or the *radio astronomy service* under specified conditions. This term shall also be applied to the frequency band concerned.
assignment (of a radio frequency or radio frequency channel)	Authorization given by an administration for a radio *station* to use a radio frequency or radio frequency channel under specified conditions.
inter-satellite service	A radiocommunication service providing links between artificial satellites.
Earth exploration-satellite service	A radiocommunication service between earth stations and one or more space stations, which may include links between space stations, in which: – information relating to the characteristics of the Earth and its natural phenomena, including data relating to the state of the environment, is obtained from active sensors or passive sensors on Earth satellites; – similar information is collected from airborne or Earth-based platforms; – such information may be distributed to earth stations within the system concerned; – platform interrogation may be included. This service may also include feeder links necessary for its operation.
radiocommunication service	A service involving the transmission, *emission* and/or reception of *radio waves* for specific *telecommunication* purposes.
radionavigation service	A radiodetermination service used for the purpose of radionavigation.
radionavigation-satellite service	A radiodetermination-satellite service used for the purpose of radionavigation. This service may also include feeder links necessary for its operation.
space operation service	A radiocommunication service concerned exclusively with the operation of spacecraft, in particular space tracking, space telemetry and space telecommand. These functions will normally be provided within the service in which the space station is operating.
space research service	A radiocommunication service in which spacecraft or other objects in space are used for scientific or technological research purposes.
station	One or more transmitters or receivers or a combination of transmitters and receivers, including the accessory equipment, necessary at one location for carrying on a radiocommunication service, or the radio astronomy service.

Table 4-2: Cross-Link Frequency Options: Regulatory Considerations

Frequency Band	Space Cross Link Allocation*	Notes
400.15-401 MHz	SPACE RESEARCH (space-to-Earth)	The band is also allocated to the space research service in the space-to-space direction for communications with manned space vehicles.
410-420 MHz	SPACE RESEARCH (space-to-space)	Cross-links limited to communications within 5 km of an orbiting, manned space vehicle
460-470 MHz	Via footnote **S5.289**: Earth exploration-satellite service (space-to-Earth)	Subject to not causing harmful interference to stations operating in accordance with the Table; only applicable for space-to-Earth
902-928 MHz	None	Industrial, Scientific and Medical (ISM) Band
1690 - 1710 MHz	Via footnote **S5.289**: Earth exploration-satellite service (space-to-Earth)	Subject to not causing harmful interference to stations operating in accordance with the Table
2025 - 2110 MHz	SPACE OPERATION (space-to-space) EARTH EXPLORATION-SATELLITE (space-to-space) SPACE RESEARCH (space-to-space)	TDRSS forward service operates in this band Frequency assignments for wideband operations (> 6 MHz) may not be authorized due to the intense use of this band (>500 stations registered in this band)
2200 - 2290 MHz	SPACE OPERATION (space-to-space) EARTH EXPLORATION-SATELLITE (space-to-space) SPACE RESEARCH (space-to-space)	TDRSS return service operates in this band Frequency assignments for wideband operations (> 6 MHz) may not be authorized due to the intense use of this band (>1000 stations registered in this band)
2400 - 2500 MHz	None (Mobile Satellite in 2483.5-2500 MHz)	Industrial, Scientific and Medical (ISM) Band
13.75 – 14.3 GHz	Space Research	Geostationary space stations in the space research service are limited to those planned prior to 31 January 1992 (e.g., TDRSS) > 3500 stations registered in this band, mostly fixed satellite service systems
14.5 – 15.35 GHz	Space Research	The 14.5-15.35 GHz band is on the agenda of WRC-03 for possible upgrade to primary status < 120 space stations registered in this band
22.55 - 23.55 GHz	INTER-SATELLITE	• Band used by Iridium • TDRSS H, I, J forward band
24.45 - 24.75 GHz	INTER-SATELLITE	
25.25 - 27.5 GHz	INTER-SATELLITE	• Limited to space research and Earth exploration-satellite applications. • TDRSS H, I, J return band
32 - 33 GHz	INTER-SATELLITE SPACE RESEARCH (deep space) (space-to-Earth) (32-32.3 GHz portion) RADIONAVIGATION	WRC-03 will review the allocations in 32-32.3 GHz since the coexistence of these two services may not lead to satisfactory operations (i.e., there is a significant possibility for interference). NASA supports the suppression of the allocation to the ISS in the 32.0 – 32.3 GHz band.

Frequency Band	Space Cross Link Allocation*	Notes
33-33.4 GHz	RADIONAVIGATION	
59.3 - 64 GHz	INTER-SATELLITE	
65 - 71 GHz	INTER-SATELLITE	
Several bands above 120 GHz	INTER-SATELLITE	
Infra red	No allocations	ITU does not currently allocate frequencies >300 GHz
Optical	No allocations	ITU does not currently allocate frequencies >300 GHz

* Primary allocations listed by CAPITAL letters; secondary in lower case.

4.3.2 SFCG Recommendations

The Space Frequency Coordination Group (SFCG)[1] has adopted several resolutions and recommendations related to the operation of inter-satellite links.

Resolution 14-1R1 resolves that if non-data relay systems use the 22.55-23.55 GHz band in the inter-satellite service (ISS) these systems should use the 22.55 - 22.81 GHz portion of the band. Data Relay Satellite (DRS) forward links will operate in the 23.12 - 23.55 GHz portion of the 22.55-23.55 GHz band, including NASA's next generation Tracking and Data Relay Satellite (TDRS). In addition, Iridium, the low-earth orbiting mobile satellite system, operates ISS links in the 23.19-23.37 GHz Band. Consequently, it is recommended that non-relay satellite cross-links seek assignments within the recommended 22.55 - 22.81 GHz portion of the band.

Recommendation 15-2R2 states, "that the implementation of proximity operation communication links in the 25.25 - 27.5 GHz band be constrained to the sub-bands 25.25-25.60 GHz and 27.225-27.5 GHz." While specific distributed spacecraft and formation flying cross-links may not be considered "proximity links," the general guidance should be considered to avoid interference with data relay satellites operating in other portions of the band.

During its last meetings in September and October 2001, the SFCG adopted a provisional recommendation (Recommendation 21-1) concerning cross-link frequencies that recommends:

1. that frequency bands allocated to the Radionavigation-Satellite Service (RNSS) below 6 GHz not be used for transmissions by formation flying systems;
2. that formation flying systems operating below 20,000 km utilise available GNSS signals for position and attitude determination whenever practicable;
3. that, for planning purposes, for intersatellite communications and navigation requirements, reference be made to the table of frequency bands shown in the annex to this Recommendation [Table 4-3];
4. that, to avoid inter-system interference problems, agencies coordinate their design choices for systems planned to operate in the same spatial region.

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1 The Space Frequency Coordination Group (SFCG), which is composed of national and international space agencies, provides a forum for multilateral discussion and coordination of spectrum matters of mutual interest concerning space research, space operations, earth exploration and meteorological satellite missions, or related applications.

Table 4-3: Frequency Bands Suitable For Implementing Cross-Links In Multiple Spacecraft "Formation Flying" Systems

BAND	FREQUENCY RANGE	SERVICE	COMMENTS
S	2025 - 2110 MHz 2200 - 2290 MHz	SRS (space- to- space) SRS (space- to- space)	
Ku	13. 75 – 14. 3 GHz 14. 5 – 15. 35 GHz	srs srs	These allocations are secondary
Ka	22. 55 – 23. 55 GHz 25. 5 – 27. 0 GHz 32. 3 – 33. 4 GHz	ISS ISS ISS, RNSS	
W	59 – 64 GHz 65 – 71 GHz	ISS ISS	

4.4 Existing Assignments and the Interference Potential

4.5 Recommended Frequency Bands & Regulatory Guidelines

The choice of frequency band for use by science missions employing crosslinks depends upon the technical and science criteria and constraints (including availability of hardware), the regulatory environment, and the overall operations of crosslinks.

First, the overall operations of crosslinks requires an estimated 120 MHz of spectrum to avoid interference and provide sufficient frequencies for missions (see Section 3). Consequently, the existing frequency allocations provide sufficient spectrum to accommodate this need, but frequency bands below 20 GHz do not provide sufficient bandwidth alone.

Second, the regulatory environment provides many bands, with varying degrees of constraints, that are appropriate for crosslinks. Section 4.3 discusses these constraints.

Third, the system designer needs to consider the availability of hardware and the technical characteristics of the frequency bands (e.g., antenna design, propagation) when choosing a frequency for implanting crosslinks. Because it is useful to provide flexibility to the system designer, several frequency bands should be available.

Taking into account each of these considerations, the preferred bands for implementing inter-satellie cross-links are listed in Table 4-4. Since significant development of short-range equipment is being explored in the 59.3-64 GHz and 65-71 GHz frequency bands, these bands are also viable but should only be considered for very short range applications.

Finally, although these preferred bands provide some flexibility to mission designers, missions may require frequencies in lower portions of the spectrum, for example at UHF, to take advantage of the propagation (lower loss) and equipment characteristics. For these additional bands to become widely acceptable, regulatory changes (e.g., primary or secondary allocations) may be required.

Table 4-4: Preferred Frequency Bands for Science Inter-Satellite (Crosslink) Communications

Band	Frequency Band	Allocation Status*
S	2025 – 2110 MHz	SPACE OPERATION EARTH EXPLORATION SATELLITE SPACE RESEARCH
	2200 – 2290 MHz	SPACE OPERATION EARTH EXPLORATION SATELLITE SPACE RESEARCH
Ku	14.5 – 15.35 GHz	Space Research (The 14.5-15.35 GHz band is on the agenda of WRC-03 for possible upgrade to primary status)
Ka	22.55 – 23.55 GHZ	INTER-SATELLITE
	25.25 – 27.5 GHz	INTER-SATELLITE

* Primary allocations listed by CAPITAL letters; secondary in lower case.

Appendix A Distributed Mission Survey Overview

This crosslink spectrum allocation survey report is based on a high-level assessment of the distributed spacecraft missions currently under consideration for the 2001 to 2020 timeframe. The evaluation process used to make the survey of distributed spacecraft missions is shown in Figure A-1. This process is a generalized variant of that presented in Figure 2-3. The primary source of information for this process is the descriptions available at mission Internet sites. Steps 1 through 5 provide an overview of the procedures taken with the mission descriptions relative to extracting and deriving information that supports the crosslink communications assessments made in this survey. Since most missions provide little information about crosslink communications requirements, various possibilities arise for the crosslinks given costs and physical constraints. One of the results of this evaluation process was to provide possible communications options that could be used to satisfy the sketchy mission descriptions. The mission crosslink parameters, both specified and derived, which comprise the output of this process, are summarized in Tables A-1 and A-2, respectively.

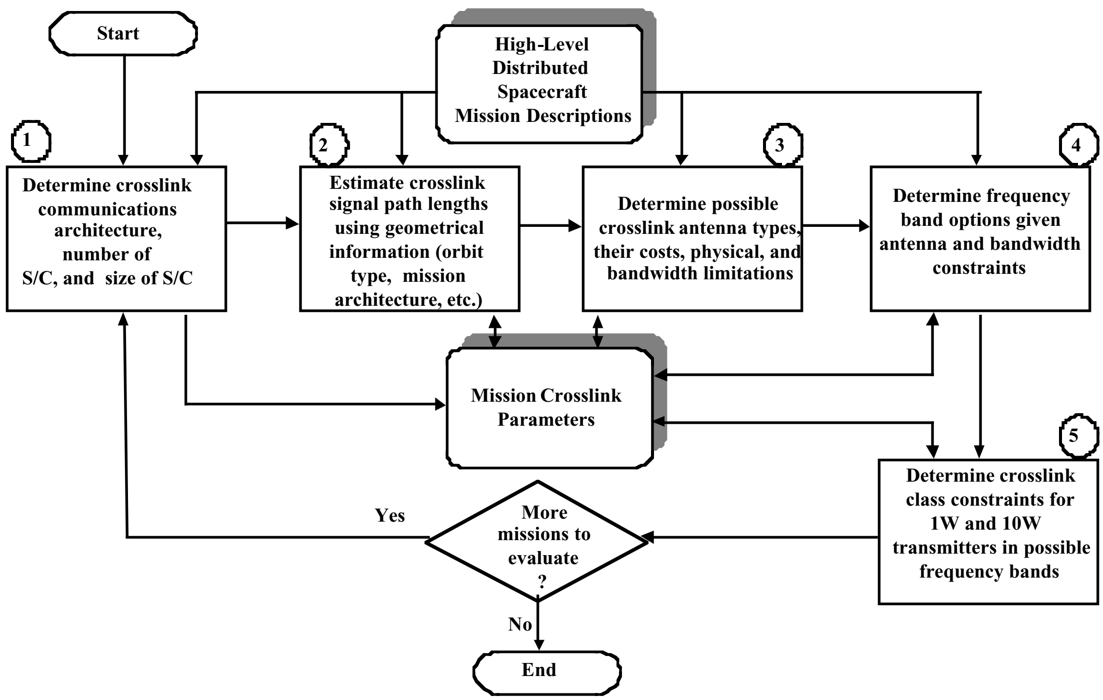

Figure A-1 Distributed Spacecraft Mission Crosslink Communications Evaluation Process

Table A-1 contains a list of distributed spacecraft missions and certain attributes associated with the mission. This information is extracted from the mission descriptions. Mission type characterizes each mission in terms of either spatial position or technology demonstrator. The planned launch dates provide the temporal information needed to placed the mission within the 2000-2020 time line. The number of spacecraft provides a perspective on the scale of the mission from a crosslink communications perspective. The spacecraft communications architecture indicates whether or not crosslinks will provide the means of inter-spacecraft communications for the mission. In some instances, mission information was not available for the for all the categories presented in Table A-1. When information could not be obtained, N/A was inserted in the table entry to indicate not available. Formation flying missions architectures that were not sufficiently described in terms of either centralized or distributed topologies were categorized as distributed.

Table A-2 contains distributed spacecraft mission assessment information extracted from the mission descriptions as well as that derived by applying technological and physical constraints to the mission descriptions. Since the information presented in the mission descriptions were not standardized, the same process could not be applied in exactly the same manner to arrive at the assessment for a given mission. Derivations followed variants of the assessment process shown in Figure 2-3. N/A entries in Table A-2 implies that the information is not available in the mission descriptions or that not enough information was available to support deriving the information in the table entry.

In general, the estimated spacecraft size and the geometrical characteristics presented in Table A-2 lead to crosslink signal path length estimates are extracted from the mission description. Antenna cost is related to spacecraft size and cost that place constraints on the type of a crosslink antenna that a mission can reasonably use. For example, low cost missions with small spacecraft sizes cannot support antennas that require high operations overhead. Antennas have intrinsic bandwidth limitations that further restricts their use in a given mission scenario to certain frequency bands. The power restrictions that are placed on the crosslinks in this analysis assume the trend towards low power. As such, crosslinks were considered with transmitters on the orders of 1W and 10W. The class limits shown in Table A-2 represent the maximum bandwidth and range combinations presented in Table 2-1 that satisfied by the link budget calculations. Classes with lower bandwidths and shorter signal path lengths are automatically satisfied. These powers were used in link budget calculations to derive the maximum data rate and signal pathlength crosslink class options for all of the antenna options available to a mission in the UHF, S, X, Ku, K, Ka,V and W frequency bands. Communications parameters that underlie the link budget results presented in Table A-2 are modulation type, bit error rate, and system temperature. Binary Phase Shift Keyed (BPSK) modulation was used with a bit error rate of 10^{-5}. The system temperature was assumed to be 500 K. Forward Error Correction (FEC) was not used.

Table A-1 Distributed Spacecraft Mission Survey Summary

Mission ID	Mission Name	Mission Type*	Planned Launch Date**	No. of S/C**	Inter-spacecraft Crosslink Communications Architecture**
01	New Millennium Program (NMP) Earth Observing-1	Earth Science	2000	2	None
02	Gravity Recovery and Climate Recovery (GRACE)	Earth Science	2001	2	DFF
03	University Nanosats/Air Force Research Laboratory Nanosat 1	Technology Demonstrator	2003	3	DFF
04	University Nanosats/Air Force Research Laboratory Nanosat 2	Technology Demonstrator	2003	3	DFF
05	NMP ST-5 Nanosat Constellation Trailblazer	Space Science	2003	3	DFF
06	Techsat-21/AFRL	Technology Demo	2004	3	DFF
07	Auroral Multiscale Mission (AMM)/APL	Space Science/SEC	2004	4	DFF
08	ESSP-3-Cena (w/ Aqua)	Earth Science	2004	2	None
09	Starlight (ST-3)	Space Science/ASO	2005	2	CFF
10	Magnetospheric Multiscale (MMS)	Space Science/SEC	2005	4	DFF
11	MAGnetic Imaging Constellation (MAGIC)	Space Science	2006	7	DFF
12	COACH	Earth Science	2006	2 – 3	C
13	Global Precipitation Mission (EOS-9)	Earth Science	2007	8	DFF
14	Geospace Electrodynamic Connections (GEC)	Space Science/SEC	2007	4	DFF
15	Constellation-X	Space Science/SEU	2008	4	DFF
16	Magnetospheric Constellation (DRACO)	Space Science/SEC	2008	50 to 100 nanosats	None
17	Laser Interferometer Space Antenna (LISA)	Space Science/SEU	2011	3 S/C 5 million km apart	DFF
18	DARWIN Space Infrared Interferometer/European Space Agency	Space Science	2014	7 S/C & 8th S/C as the master comm. S/C	CFF
19	Leonardo (GSFC)	Earth Science	2010	4 – 8	N/A
20	Stellar Imager (SI)	Space Science/ASO	2011	10 to 30 S/C	CFF
21	Astronomical Low Frequency Array (ALFA)/Explorers	Space Science	N/A	16 S/C cluster	None
22	MAXIM Pathfinder	Space Science/SEU	2005+	2	CFF
23	Living with a Star (LWS)	Space Science	2005+	8	CFF
24	Soil Moisture and Ocean Salinity Observing Mission (EX-4)	Earth Science	2005/2008	1	None

25	Time-Dependent Gravity Field Mapping Mission (EX-5)	Earth Science	2005+	N/A	N/A
26	Vegetation Recovery Mission (EX-6)	Earth Science	2005+	N/A	N/A
27	Cold Land Processes Research Mission (EX-7)	Earth Science	2005+	N/A	N/A
28	Hercules	Space Science/SEC	2005+	36	DFF
29	Orion Constellation Mission	Space Science/SEC	2005+	42	N/A
30	Submillimeter Probe of the Evolution of Cosmic Structure (SPECS)	Space Science/SEU	2015	3	N/A
31	Planet Imager (PI)	Space Science/ASO	2015+	6	CFF
32	MAXIM X-ray Interferometry Mission	Space Science/SEU	2016	34	CFF
33	Solar Flotilla, IHC, OHRM, OHRI, ITM, IMC, DSB Con	Space Science/SEC	2015+	4	DFF
34	NASA Goddard Space Flight Center Earth Sciences Vision	Earth Science	2015+	N/A	N/A
35	NASA Institute of Advanced Concepts/Very Large Optics for the Study of Extrasolar Terrestrial Planets	Space Science	2015+	N/A	N/A
36	NASA Institute of Advanced Concepts /Ultra-high Throughput X-Ray Astronomy Observatory with a New Mission Architecture	Space Science	2015+	N/A	DFF
37	NASA Institute of Advanced Concepts /Structureless Extremely Large Yet Very Lightweight Swarm Array Space Telescope	Space Science	2015+	N/A	N/A
38	Active Tropospheric Ozone & Moisture Sounder (ATOMS) Constellation	Earth Science	2005	12	C
39	SMART-2	Technology Demo	2006	2	DFF

* ASO – Astronomical Search for Origins
* SEC – Sun Earth Connections
* SSE – Solar System Exploration
* SEU – Structure and Evolution of the Universe

** None – Implies Ground Link only
** C – Constellation
** CFF – Centralized Formation Flying
** DFF – Distributed Formation Flying
** N/A – Information Not Available

Table A-2 Distributed Spacecraft Mission Assessments

Mission ID	Mission Name	Estimated S/C Size *	No. of S/C	Geometry Considerations	Antenna Cost	Available Antenna Type	Max BW Supported by Antenna	Possible Cross Link Freq Bands	1W Class Limits	10 W Class Limits
01	EO-1	Large	2	705km, Circular Sun-synchronous earth orbit, 98.7 deg inclination	Low Medium High	Helix Patch Parabolic	Narrow Medium High	X** X** X**	N/A***	N/A
02	GRACE	Large	2	Similar to CHAMP at ~460km earth orbit	Medium High "	Patch Parabolic Horn	Medium High High	K** K** K**	5a, 4b 5b, 2c 5b, 2c	5b 5b, 3c 5b, 3c
03	Nanosat-1	Small	3	N/A	Low " " "	Mono Yagi Mono Helix	Narrow " " "	UHF UHF S X	3b 3b 4a, 2b 3a, 1b	3b 3b 4a, 3b 4a, 2b
04	Nanosat-2	Small	3	N/A	Low " " "	Mono Yagi Mono Helix	Narrow " " "	UHF UHF S X	3b 3b 4a, 2b 3a, 1b	3b 3b 4a, 3b 4a, 2b
05	ST-5	Nanosats	3	N/A	Low " " "	Mono Yagi Mono Helix	Narrow " " "	UHF UHF S X	3b 3b 4a, 2b 3a, 1b	3b 3b 4a, 3b 4a, 2b
06	Techsat-21/AFRL	Small (10-100kgs)	3	600km, Circular orbit, FF	Low " " "	Mono Yagi Mono Helix	Narrow " " "	UHF UHF S X	3b 3b 4a, 2b 3a, 1b	3b 3b 4a, 3b 4a, 2b
07	AMM/APL	Medium Class Explorer	4	Closely Spaced Near Polar earth orbit	Medium " " " " " "	Helix Helix Patch Patch Patch Patch Patch	Narrow " Medium " " " "	UHF S S X Ku K Ka	3b 4b 4b 5a, 4b 5a, 4b 5a, 4b 5a, 4b	3b 4b 4b 5b 5b 5b 5b

08	ESSP-3-Cena (w Aqua)	Large (560kgs)	2	705km, Circular Sun- synchronous earth orbit	High “ “ “ “ “ “ “ “ “ “ ” ”	Phased Parabolic Parabolic Parabolic Horn Parabolic Horn Parabolic Horn Parabolic Horn Parabolic Horn	Medium High “ ” ” ” ” ” ” ” ” ” ”	S S X Ku Ku K K Ka Ka V V W W	N/A	N/A
09	Starlight (ST-3)	Large	2	Orbit around Sun matching earth orbit behind earth by 10 million miles, FF, 200 km (mother – daughter configuration)	Low “ Medium	Mono Yagi Helix	Narrow “ “	UHF** UHF** UHF**	3b 3b 3b	3b 3b 3b
10	MMS	Description implies small cluster of S/C	4	Tetrahedral Config. Identical S/C flying in 4 different earth orbits, FF, 1km to several Re apart	Low “ ” ” Medium “ ” ” ” ” ” High “ ” ” ” ” ” ” ” ” ” ” ”	Mono Yagi Mono Helix Helix Helix Patch Patch Patch Patch Patch Phased Parabolic Parabolic Parabolic Horn Parabolic Horn Parabolic Horn Parabolic Horn Parabolic Horn	Narrow “ “ “ Narrow “ Medium “ “ “ “ Medium High “ ” ” ” ” ” ” ” ” ” ”	UHF UHF S X UHF S S X Ku K Ka S S X Ku Ku K K Ka Ka V V W W	3b 3b 4a, 2b 3a, 1b 3b 4b 4b 5a, 4b 5a, 4b 5a, 4b 5a, 4b 4b 4b 5b, 1c 5b, 1c 5b, 1c 5b, 2c 5b, 2c 5b, 2c 5b, 2c 5b 5b 5b, 3c 5b, 3c	3b 3b 4a, 3b 4a, 2b 3b 4b 4b 5b 5b 5b 5b 4b 4b, 1c 5b, 2c 5b, 2c 5b, 2c 5b, 3c 5b, 3c 5b, 3c 5b, 3c 5b, 1c 5b, 1c 5b, 4c 5b, 4c

11	MAGIC	Small	7		Low	Mono	Narrow	UHF	3b	3b
					"	Yagi	"	UHF	3b	3b
					"	Mono	"	S	4a, 2b	4a, 3b
					"	Helix	"	X	3a, 1b	4a, 2b
					Medium	Helix	Narrow	UHF	3b	3b
					"	Helix	"	S	4b	4b
					"	Patch	Medium	S	4b	4b
					"	Patch	"	X	5a, 4b	5b
					"	Patch	"	Ku	5a, 4b	5b
					"	Patch	"	K	5a, 4b	5b
					"	Patch	"	Ka	5a, 4b	5b
					High	Phased	Medium	S	4b	4b
					"	Parabolic	High	S	4b	4b, 1c
					"	Parabolic	"	X	5b, 1c	5b, 2c
					"	Parabolic	"	Ku	5b, 1c	5b, 2c
					"	Horn	"	Ku	5b, 1c	5b, 2c
					"	Parabolic	"	K	5b, 2c	5b, 3c
					"	Horn	"	K	5b, 2c	5b, 3c
					"	Parabolic	"	Ka	5b, 2c	5b, 3c
					"	Horn	"	Ka	5b, 2c	5b, 3c
					"	Parabolic	"	V	5b	5b, 1c
					"	Horn	"	V	5b	5b, 1c
					"	Parabolic	"	W	5b, 3c	5b, 4c
					"	Horn	"	W	5b, 3c	5b, 4c
12	COACH	N/A	2 – 3	N/A	N/A	N/A	N/A	N/A	N/A	N/A
13	GPM – (EOS-9)	Small	8	Sun synchronous polar orbit at 600km	Low	Mono	Narrow	UHF	3b	3b
					"	Yagi	"	UHF	3b	3b
					"	Mono	"	S	4a, 2b	4a, 3b
					"	Helix	"	X	3a, 1b	4a, 2b

14	GEC	Large	4		Low	Mono	Narrow	UHF	3b	3b
					“	Yagi	“	UHF	3b	3b
					”	Mono	“	S	4a, 2b	4a, 3b
					”	Helix	“	X	3a, 1b	4a, 2b
					Medium	Helix	Narrow	UHF	3b	3b
					“	Helix	“	S	4b	4b
					”	Patch	Medium	S	4b	4b
					”	Patch	“	X	5a, 4b	5b
					”	Patch	“	Ku	5a, 4b	5b
					”	Patch	“	K	5a, 4b	5b
					”	Patch	“	Ka	5a, 4b	5b
					High	Phased	Medium	S	4b	4b
					“	Parabolic	High	S	4b	4b, 1c
					”	Parabolic	“	X	5b, 1c	5b, 2c
					”	Parabolic	”	Ku	5b, 1c	5b, 2c
					”	Horn	”	Ku	5b, 1c	5b, 2c
					”	Parabolic	”	K	5b, 2c	5b, 3c
					”	Horn	”	K	5b, 2c	5b, 3c
					”	Parabolic	”	Ka	5b, 2c	5b, 3c
					”	Horn	”	Ka	5b, 2c	5b, 3c
					”	Parabolic	”	V	5b	5b, 1c
					”	Horn	”	V	5b	5b, 1c
					”	Parabolic	”	W	5b, 3c	5b, 4c
					”	Horn	”	W	5b, 3c	5b, 4c
15	Constellation – X	Small	4	Modeled after HTXS mission – L2 orbit	Low	Mono	Narrow	UHF	3b	3b
					“	Yagi	“	UHF	3b	3b
					“	Mono	“	S	4a, 2b	4a, 3b
					“	Helix	“	X	3a, 1b	4a, 2b
16	DRACO	Nanosats	50 to 100 nanosats	Elliptical earth orbits w S/C Constellation at <15Re, 15 – 25 Re, 25 – 35 Re ranges, 1 Re over a 25 Re domain (No Xlink because of ground processing)	Low	N/A	N/A	N/A	N/A	N/A

17	LISA		3 S/C 5 million km apart	Solar orbit	High “ ” ” ” ” ” ” ” ” ” ” ”	Phased Parabolic Parabolic Parabolic Horn Parabolic Horn Parabolic Horn Parabolic Horn Parabolic Horn	Medium High “ ” ” ” ” ” ” ” ” ” ”	S S X Ku Ku K K Ka Ka V V W W	4b 4b 5b, 1c 5b, 1c 5b, 1c 5b, 2c 5b, 2c 5b, 2c 5b, 2c 5b 5b 5b, 3c 5b, 3c	4b 4b, 1c 5b, 2c 5b, 2c 5b, 2c 5b, 3c 5b, 3c 5b, 3c 5b, 3c 5b, 1c 5b, 1c 5b, 4c 5b, 4c
18	DARWIN	1.7 meters in diameter. Since these are bigger than nanosats these are Medium sats	7 S/C & 8th S/C as the master comm. S/C	FF, 1.5 million km from Earth opposite direction from Sun at L2, 100 to 500 meters, RF ranging system, GPS like technology, 7 in hex configuration with one in center and master away	Low “ “ “	Mono Yagi Mono Helix	Narrow “ “ “	UHF UHF S X	3b 3b 4a, 2b 3a, 1b	3b 3b 4a, 3b 4a, 2b
19	Leonardo (GSFC)	N/A	4 – 8	N/A	N/A	N/A	N/A	N/A	N/A	N/A
20	Stellar Imager (SI)	Nanosats (10 kgs)	10 to 30 S/C	FF at L2, Option1: 9 primary and 10th collector Option2: 30 S/C, >500 m distance each	Low “ “ “	Mono Yagi Mono Helix	Narrow “ “ “	UHF UHF S X	3b 3b 4a, 2b 3a, 1b	3b 3b 4a, 3b 4a, 2b
21	ALFA	N/A	16 S/C cluster	Distant retrograde orbit around the moon, No X-link from what the text says	N/A	N/A	N/A	N/A	N/A	N/A

22	MAXIM Pathfinder	Large	2	Drift away orbit from earth	Low	Mono	Narrow	UHF	3b	3b
					“	Yagi	“	UHF	3b	3b
					”	Mono	“	S	4a, 2b	4a, 3b
					”	Helix	“	X	3a, 1b	4a, 2b
					Medium	Helix	Narrow	UHF	3b	3b
					“	Helix	“	S	4b	4b
					”	Patch	Medium	S	4b	4b
					”	Patch	“	X	5a, 4b	5b
					”	Patch	“	Ku	5a, 4b	5b
					”	Patch	“	K	5a, 4b	5b
					”	Patch	“	Ka	5a, 4b	5b
					High	Phased	Medium	S	4b	4b
					“	Parabolic	High	S	4b	4b, 1c
					”	Parabolic	“	X	5b, 1c	5b, 2c
					”	Parabolic	”	Ku	5b, 1c	5b, 2c
					”	Horn	”	Ku	5b, 1c	5b, 2c
					”	Parabolic	”	K	5b, 2c	5b, 3c
					”	Horn	”	K	5b, 2c	5b, 3c
					”	Parabolic	”	Ka	5b, 2c	5b, 3c
					”	Horn	”	Ka	5b, 2c	5b, 3c
					”	Parabolic	”	V	5b	5b, 1c
					”	Horn	”	V	5b	5b, 1c
					”	Parabolic	”	W	5b, 3c	5b, 4c
					”	Horn	”	W	5b, 3c	5b, 4c

23	LWS	Large	8	450km circular	Low	Mono	Narrow	UHF	3b	3b
				earth orbits, 6	“	Yagi	“	UHF	3b	3b
				polar S/C and 2	”	Mono	“	S	4a, 2b	4a, 3b
				S/C at 30 deg	”	Helix	“	X	3a, 1b	4a, 2b
				inclination	Medium	Helix	Narrow	UHF	3b	3b
					“	Helix	“	S	4b	4b
					”	Patch	Medium	S	4b	4b
					”	Patch	“	X	5a, 4b	5b
					”	Patch	“	Ku	5a, 4b	5b
					”	Patch	“	K	5a, 4b	5b
					”	Patch	“	Ka	5a, 4b	5b
					High	Phased	Medium	S	4b	4b
					“	Parabolic	High	S	4b	4b, 1c
					”	Parabolic	“	X	5b, 1c	5b, 2c
					”	Parabolic	”	Ku	5b, 1c	5b, 2c
					”	Horn	”	Ku	5b, 1c	5b, 2c
					”	Parabolic	”	K	5b, 2c	5b, 3c
					”	Horn	”	K	5b, 2c	5b, 3c
					”	Parabolic	”	Ka	5b, 2c	5b, 3c
					”	Horn	”	Ka	5b, 2c	5b, 3c
					”	Parabolic	”	V	5b	5b, 1c
					”	Horn	”	V	5b	5b, 1c
					”	Parabolic	”	W	5b, 3c	5b, 4c
					”	Horn	”	W	5b, 3c	5b, 4c
24	EX-4	Large	1	757 km Sun-synchronous earth orbit	N/A	N/A	N/A	N/A	N/A	N/A
25	EX-5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
26	EX-6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
27	EX-7	N/A	N/A	Low altitude Sun-synchronous earth orbit	N/A	N/A	N/A	N/A	N/A	N/A

28	Hercules	Small	36	S/C hover near apogee, S/C are 10 Re from earth, S/C separated by 1 Re	Medium “ ” ” ” ” ” High “ ” ” ” ” ” ” ” ” ” ” ”	Helix Helix Patch Patch Patch Patch Patch Phased Parabolic Parabolic Parabolic Horn Parabolic Horn Parabolic Horn Parabolic Horn Parabolic Horn	Narrow “ Medium “ “ “ “ Medium High “ ” ” ” ” ” ” ” ” ” ”	UHF S S X Ku K Ka S S X Ku Ku K K Ka Ka V V W W	3b 4b 4b 5a, 4b 5a, 4b 5a, 4b 5a, 4b 4b 4b 5b, 1c 5b, 1c 5b, 1c 5b, 2c 5b, 2c 5b, 2c 5b, 2c 5b 5b 5b, 3c 5b, 3c	3b 4b 4b 5b 5b 5b 5b 4b 4b, 1c 5b, 2c 5b, 2c 5b, 2c 5b, 3c 5b, 3c 5b, 3c 5b, 3c 5b, 1c 5b, 1c 5b, 4c 5b, 4c
29	Orion	Small	42	3 inner petal earth orbits (2*6.5Re) w 10S/C per orbit = 30, 3 outer petal earth orbits (2*12Re) w 4S/C per orbit = 12, (S/C will be separated by more than 1000km if Xlink is there	Medium “ ” ” ” ” ” High “ ” ” ” ” ” ” ” ” ” ” ”	Helix Helix Patch Patch Patch Patch Patch Phased Parabolic Parabolic Parabolic Horn Parabolic Horn Parabolic Horn Parabolic Horn Parabolic Horn	Narrow “ Medium “ “ “ “ Medium High “ ” ” ” ” ” ” ” ” ” ”	UHF S S X Ku K Ka S S X Ku Ku K K Ka Ka V V W W	3b 4b 4b 5a, 4b 5a, 4b 5a, 4b 5a, 4b 4b 4b 5b, 1c 5b, 1c 5b, 1c 5b, 2c 5b, 2c 5b, 2c 5b, 2c 5b 5b 5b, 3c 5b, 3c	3b 4b 4b 5b 5b 5b 5b 4b 4b, 1c 5b, 2c 5b, 2c 5b, 2c 5b, 3c 5b, 3c 5b, 3c 5b, 3c 5b, 1c 5b, 1c 5b, 4c 5b, 4c
30	SPECS (universe discovery question)	N/A	3	N/A	N/A	N/A	N/A	N/A	N/A	N/A

31	Planet Imager (PI)	Small	6	FF, 5S/C + 1S/C (combiner)	Low “ ” ”	Mono Yagi Mono Helix	Narrow “ “ “	UHF UHF S X	3b 3b 4a, 2b 3a, 1b	3b 3b 4a, 3b 4a, 2b
32	MAXIM	Small and Large	34	33 S/C and 1S/C large flying 300 miles behind	Low “ ” ”	Mono Yagi Mono Helix	Narrow “ “ “	UHF UHF S X	3b 3b 4a, 2b 3a, 1b	3b 3b 4a, 3b 4a, 2b
33	Solar Flotilla	Large (9.5ftx4.27ft) 1.2 tons each	4	Polar earth orbit, pyramidal formation, 620km to 11160km	N/A	N/A	N/A	N/A	N/A	N/A
34	NASA vision	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
35	NASA very large optics	Large	N/A	JUST AN IDEA OF MISSION	N/A	N/A	N/A	N/A	N/A	N/A
36	NASA ultra high X-ray	N/A	N/A	L2, 10000 to 100000km elliptical orbit, FF, Distributed S/C	N/A	N/A	N/A	N/A	N/A	N/A
37	NASA advanced concepts	N/A	N/A	Distributed S/C system	N/A	N/A	N/A	N/A	N/A	N/A
38	ATOMS	Small	12	Low earth orbiting S/C	Medium High High	Patch Parabolic Horn	Medium High High	Ka band** Ka band** Ka band**	5a, 4b 5b, 2c 5b, 2c	5b 5b, 3c 5b, 3c

39	SMART-2	Large	2	Earth orbits	Low	Mono	Narrow	UHF	3b	3b
					"	Yagi	"	UHF	3b	3b
					"	Mono	"	S	4a, 2b	4a, 3b
					"	Helix	"	X	3a, 1b	4a, 2b
					Medium	Helix	Narrow	UHF	3b	3b
					"	Helix	"	S	4b	4b
					"	Patch	Medium	S	4b	4b
					"	Patch	"	X	5a, 4b	5b
					"	Patch	"	Ku	5a, 4b	5b
					"	Patch	"	K	5a, 4b	5b
					"	Patch	"	Ka	5a, 4b	5b
					High	Phased	Medium	S	4b	4b
					"	Parabolic	High	S	4b	4b, 1c
					"	Parabolic	"	X	5b, 1c	5b, 2c
					"	Parabolic	"	Ku	5b, 1c	5b, 2c
					"	Horn	"	Ku	5b, 1c	5b, 2c
					"	Parabolic	"	K	5b, 2c	5b, 3c
					"	Horn	"	K	5b, 2c	5b, 3c
					"	Parabolic	"	Ka	5b, 2c	5b, 3c
					"	Horn	"	Ka	5b, 2c	5b, 3c
					"	Parabolic	"	V	5b	5b, 1c
					"	Horn	"	V	5b	5b, 1c
					"	Parabolic	"	W	5b, 3c	5b, 4c
					"	Horn	"	W	5b, 3c	5b, 4c

* Criteria: Small, Medium, or Large
** Mission Specified
*** N/A- Information Not Available

Appendix B Abbreviations and Acronyms

ASO	Astronomical Search for Origins
BPSK	Binary Phase Shift Keying
CFF	Centralized Formation Flying
DFF	Distributed Formation Flying
DRS	Data Relay Satellite
DSS	Distributed Spacecraft System
FEC	Forward Error Correction
ft	Feet
GEO	Geosynchronous Earth Orbit
GHz	Gigahertz
GNSS	Global Navigation Satellite System
GSFC	Goddard Space Flight Center
HEO	High Earth Orbit
Hz	Hertz
IRAC	Interdepartment Radio Advisory Committee
ISM	Industrial, Scientific and Medical
ISS	Inter-Satellite Service
ITU	International Telecommunication Union
km	Kilometer
kbps	Kilobit per second
LEO	Low Earth Orbit
LISA	Laser Interferometer Space Antenna
MAGIC	Magnetic Imaging Constellation
MEO	Medium Earth Orbit
MDR	Maximum Data Rate
MHz	Megahertz
MMS	Magnetic Multiscale
Mbps	Megabit per second
N/A	Not Available
NASA	National Aeronautics and Space Administration
NTIA	National Telecommunications and Information Administration
PI	Planet Imager
RF	Radio Frequency
RNSS	Radionavigation-Satellite Service
S/C	Spacecraft
SEC	Sun Earth Connections
SEU	Structure and Evolution of the Universe
SFCG	Space Frequency Coordination Group
SPS	Spectrum Planning Committee
SRS	Space Research Service
SSE	Solar System Exploration
TDRS	Tracking and Data Relay Satellite
UHF	Ultra High Frequency
W	Watt